MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

The Design and Operation of a Slowfall AXCP

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ABSTRACT

Expendable current profilers (XCPs) were modified to fall slowly (<1 m s^{-1}) through the upper ocean for the Ocean Storms research program. The purposes of the modification were to improve launch and impact survival and to slow the unit significantly so more cycles of surface wave oscillations could be observed in the upper 200 m of the ocean. The device was based on a standard air-deployable XCP (AXCP) manufactured by Sippican Ocean Systems Inc. A drogue was installed on the sensor to slow its descent over a portion of the upper ocean while maintaining a sufficient spin, or rotation rate. At a preset depth, the drogue was jettisoned, and the profiler probe reverted to its normal descent and spin rates.

Forty slowfall AXCPs were deployed in late 1987. Three of these were dropped simultaneously with regular AXCPs. Nineteen units provided profile data. The success rates were 2/13, 7/13, and 10/14 for units operating on sonobuoy RF channels 12, 14, and 16, respectively. The combined success rate for the channel-14 and channel-16 units was 0.63. The probability of obtaining the channel-12 results (2 of 13), assuming a success probability of 0.63, is $<0.1\%$. These results indicate that the poor performance of the channel-12 units was due to some factor not present in the units at other frequencies. Eleven of the thirteen channel-12 probes failed to produce RF emissions or lost the signals soon after deployment. This mode of failure is unrelated to slowfall modification and suggests failure in the standard gas release and flotation bag system.

INTRODUCTION

The slowfall AXCP was developed by APL-UW for the Ocean Storms program, a multifaceted investigation conducted in the North Pacific in the fall of 1987 to investigate interactions between atmospheric disturbances and the upper ocean. Ocean Storms sought to quantify the significant variables of the ocean and atmosphere and develop theoretical models explaining their interaction.[1] Historically, such models have been limited to one dimension. The experiments conducted to support these models have likewise been one dimensional, in part because of the cost and feasibility of installing instrumentation capable of temporal correlation over a large area (50 to 250 km).

Prompted by recent advances in sensor technology, Ocean Storms sought large-scale, simultaneous measurements of ocean and atmospheric properties throughout a strong weather disturbance.

The major sensing techniques involved several types of drifting buoys, moored arrays, bottom-mounted sensors, and remote sensors on satellites and aircraft. In addition, air-deployed, expendable current profilers (AXCPs) were used to gather velocity and temperature data over a large area. The AXCP modifications to achieve slower descent rates over the upper 200 m of the water column are described here.

APPROACH

The APL-UW AXCP Slowfall Program involved the modification of a production sensor system, the air-deployable expendable current profiler (AXCP) manufactured by Sippican Ocean Systems Inc. (SOSI) of Marion, Massachusetts. Sippican manufactures a variety of expendable sensors, including bathythermographs (XBTs) and acoustic sonobuoys, both submarine and air launched. The AXCP offered a unique sensing technique for the Ocean Storms research.

The standard XCP is designed to be launched from a ship of opportunity. The ship need not be stationary, since there is no mechanical tether between it and the sensor. The entire system — consisting of a surface buoy with radio transmitter, a free-falling sensor probe, and 1500 m of wire connecting the two — is simply tossed overboard. The total package weighs about 10 kg and is 12 cm in diameter by 100 cm long. The probe is projectile shaped with a cruciform tail and ring shroud. It weighs 900 g in seawater and is approximately 5 cm in diameter by 42 cm long. Probe signals are sent up the wire and

telemetered to the ship via a radio link. This wire, commonly referred to as BT wire because of its original use in the XBT systems, has a breaking strength of about 1 lb.

Deployment consists of the following series of events, which occur within 50 s of impact with the water's surface. The cannister, being negatively buoyant, sinks, flooding the interior and the seawater-activated battery contained within. The battery provides power to fire a squib that punctures a CO_2 cartridge. The CO_2 inflates a flotation bladder and simultaneously releases the outer aluminum cannister, which then falls away under its own weight. The remaining system, buoyed up by the attached flotation bladder, floats to the surface. About 40 s later, a timer, activated at battery power-up, fires a second squib, which uncaps the end of the probe's launch tube. The probe then falls free of the surface, rotating as it descends. As it drops through the water column, it trails the fine, two-conductor (BT) wire which deploys from spools on both the probe and surface buoy. This method of wire deployment eliminates an increasing drag force and allows the probe to maintain a uniform descent speed.

The descending probe measures the ocean current electromagnetically. Essentially, the XCP measures the voltage produced by a conductor (seawater) moving through a magnetic field (the earth's magnetism) to provide an indication of ocean current velocity. The signal generated by the oceanic flow at any depth is nearly steady, but by rotating the probe as it descends this steady component is converted to a sinusoidal voltage. These signals, along with those from a temperature sensor, are amplified, converted to frequency-modulated audio signals, and sent to the surface buoy where they are used to modulate a given radio frequency for transmission to the deploying vessel. (For details of the actual sensing mechanism, see Reference 2.)

The AXCP is the same system as the ship-launched XCP, but with an added parachute decelerating system and outer aluminum tube. These modifications allow the system to be launched through normal sonobuoy launch tubes (either with a cartridge activated device or gravity launched) while the radio receiver is on board the aircraft.

SYSTEM DESIGN

Design Objective

Although the XCP measures current to a depth of 1500 m, the significant effects of an ocean storm occur in the first 200 m of the water column. Since a more slowly falling probe would have greater resolution than a normal speed one, it was desirable to reduce the XCP's descent speed in the upper water column.

The final objective was a two-speed descent: a slow descent in the upper 200 m changing to a normal descent for the remaining 1300 m. There were two reasons for not maintaining the slow descent over the entire depth. First, a slow descent for 1500 m might put the receiving aircraft out of range or exhaust the batteries; second, the RF channels would be occupied by long-lived probes (>30 min), preventing rapid deployment for fine spatial surveys. A two-speed version would provide high-resolution data in surface waters and coarse resolution in the majority of water, while transmitting for less than 10 min.

The specific objective was threefold: Design a drogue that would

    (a) reduce the descent speed from 4.5 m s^{-1} to less than 1 m s^{-1}

    (b) maintain a probe spin rate greater than 2 Hz

    (c) jettison at a specified depth.

The first task was to identify a technique that would reduce the probe's descent speed and rotation rate in the upper 200 m of water. Then a mechanism was needed to jettison the drogue at a specified time or depth and let the probe resume its normal descent and spin rates. Because the probe's depth is inferred through descent time, it is important to maintain known fall speeds even in the slowfall mode. Figure 1 shows the modified AXCP during launch and slowfall descent.

Drogue Design

Essentially there are three ways to reduce the descent speed:

    (a) increase the drag

    (b) reduce the net weight by adding flotation

    (c) develop hydrodynamic lift.
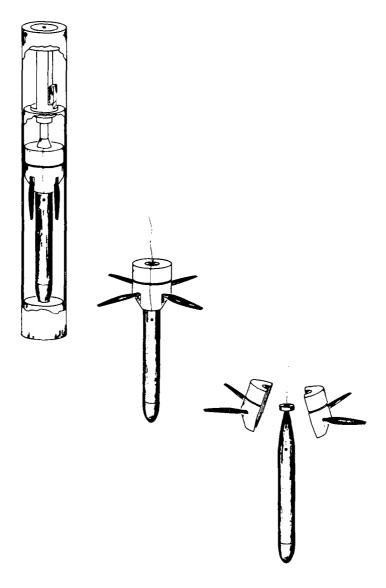
Figure 1. Modified AXCP during launch and slowfall descent.

Early design considerations focused on a combination of these three techniques. Any drogue attached to the probe would increase the drag; even a neutral density system would reduce the fall speed. However, unbalanced drag forces, or those arising from spontaneous flow separation and reattachment or large base drag forces, had to be avoided because they might cause dynamic instabilities such as a corkscrew descent path or precession in a horizontal direction.

It was decided that the only feasible technique was using small airfoils to generate both a rotational moment and some hydrodynamic lift. These airfoils, stowed flat along the body, would deploy as the probe exited the launch tube and cause it to spin as it descended. Figure 2 shows the drogue system design. Figure 3 shows the general arrangement of the slowfall probe in its launch tube.

Several variables are inherent in this system. They include the number of airfoils, the size of the airfoil, the angle of attack, and the weight of the drogue. In addressing the first and last issues, we were guided by an informative paper by Mortensen and Lange.[3] Although any balanced number of airfoils can be used, they suggested that a system of four was the most appropriate because (a) it would be less sensitive to variances in individual airfoil characteristics and (b) reasonable descent conditions could be maintained even if only three of the four foils deployed. In addition, they stated that a negatively buoyant system is more desirable than a neutrally buoyant one. This is in part because of the stability afforded by the balance of forces. A steady-state equilibrium of the hydrodynamic lift and drag and hydrostatic forces develops, which provides good inertial stability.

Two general constraints also need mentioning. First, the drogue should be placed as far downstream as possible, since its location can alter the flow of water over the probe's electrodes in unpredictable ways. Second, the probe's center of lift and drag should be as far as possible from the center of gravity to maximize the static and dynamic stability of the system. The XCP's electrode ports are approximately halfway along the probe, and the probe's center of gravity is well forward owing to a heavy zinc nose cone.

With the principal variables defined for the system, a brief analytical investigation was performed, after which an experimental test program was pursued.

Drogue Release Mechanism

Concurrent with the development of the drogue system, techniques were investigated to accomplish its release. The first was a timer-based system. Although the idea appeared workable, it required a mechanical or electronic timer and a means of starting the timer at the surface as well as a release mechanism.

We then considered using an inexpensive pressure switch to trip the release mechanism. After a market survey, samples were ordered of likely candidates, and a switch was found with suitable accuracy, consistency, weight, size, and cost.
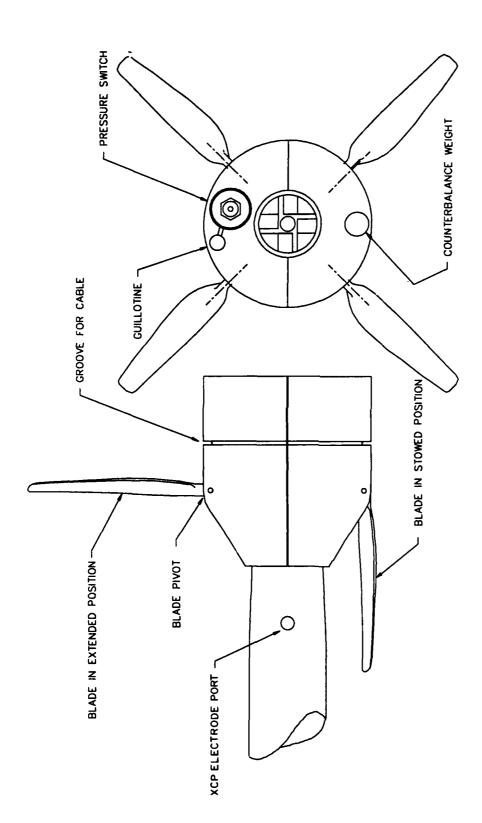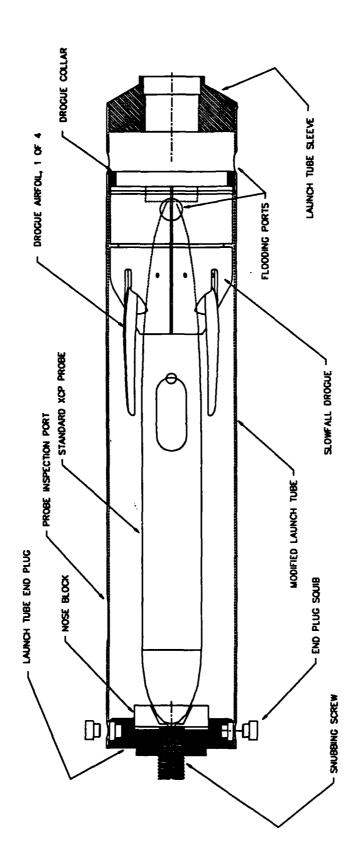
Figure 2. Drogue mechanism.

Figure 3. General arrangement of launch tube.

With the release indicator selected, techniques were examined to release the drogue. By this time, it had been determined that the drogue would clamp around the neck on the probe's afterbody just before the cruciform tail and ring shroud, and that it would be a split clam shell design held together by a tensile band. The drogue would be jettisoned by severing this tensile band, allowing the two halves to simply fall away and the probe to resume its normal descent.

Two techniques were investigated. One involved using a hot wire, either as part of the band or as a cutting surface, to melt through a low-melting-point line such as monofilament nylon. The other involved using an explosive guillotine. This is a small, reliable, relatively inexpensive device which fires a small explosive charge in an enclosed chamber. The resulting expansion of gas drives a cutting ram that can easily cut through small-diameter steel cable. It was decided to use the guillotine system, as it was available off the shelf, was small and lightweight, and could be fired with the current from a small power source. A schematic of the final drogue release system is shown in Figure 4.

The guillotine was selected on the basis of size, cable cutting capacity, and power requirement. The main concern was the power requirement, as the battery, whether alkaline or lithium based, must be small. The selected guillotine, manufactured by Holex Inc. of Hollister, California, requires a current >1 A for 25 ms or more to fire. Although a lithium-based battery could provide the necessary current as well as an excellent shelf life, lithium batteries were rejected for two reasons. One, they must be aircraft certified, and the probes would be launched from a P-3 Orion aircraft. Two, lithium batteries can "go to sleep" after storage; in fact, this is what gives them their excellent shelf life.

Tests conducted with Duracell AA and AAA alkaline cells and a dummy load (Figure 5) showed both cells were able to generate the current needed to fire the guillotine. The larger AA cell could do so repeatedly, over 25 times with a short recovery interval between tests. The more robust AA cell was chosen because it was more likely to provide a sufficient current after 2 or 3 months on the shelf. Solder tabs were added for electrical connection to the battery.

In keeping with the expendable nature of the system, a pressure housing encasing the cell, guillotine, and switch was abandoned in favor of simple blind holes filled with a rigid-setting, encapsulating epoxy compound. This solved the problem of sealing the

WHITMAN PRESSURE SWITCH

END VIEW

GROOVE FOR CABLE

AA-CELL W/ SOLDER TABS

WIRE SLOT

VIEW B-B

VIEW A-A
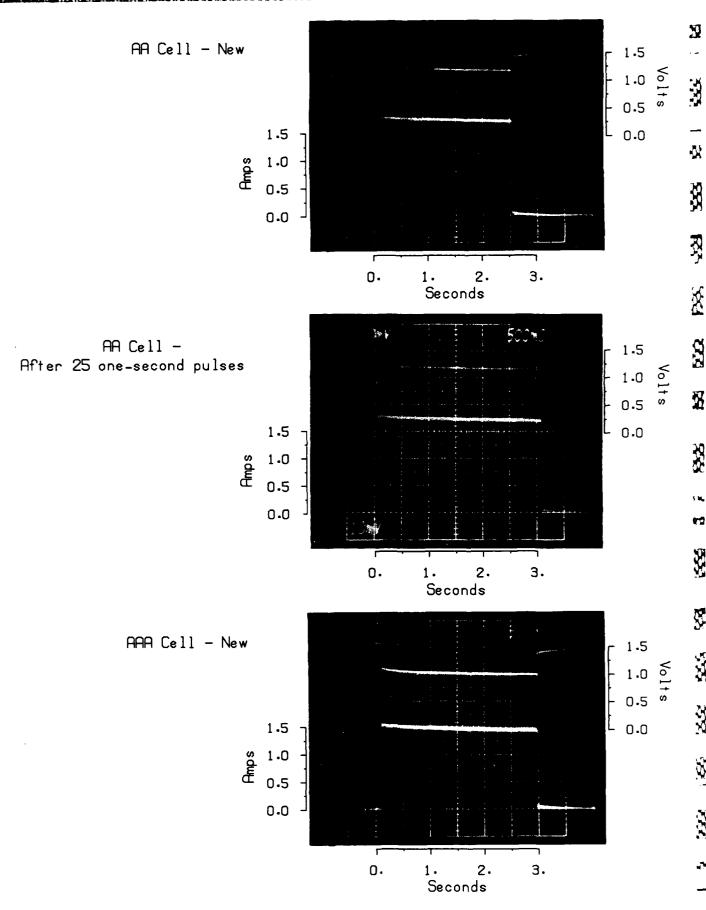
HOLEX GUILLOTINE

MASTER AIRSCREW 12X6 BLADE

VIEW C-C

VIEW D-D

XCP AFTERBODY
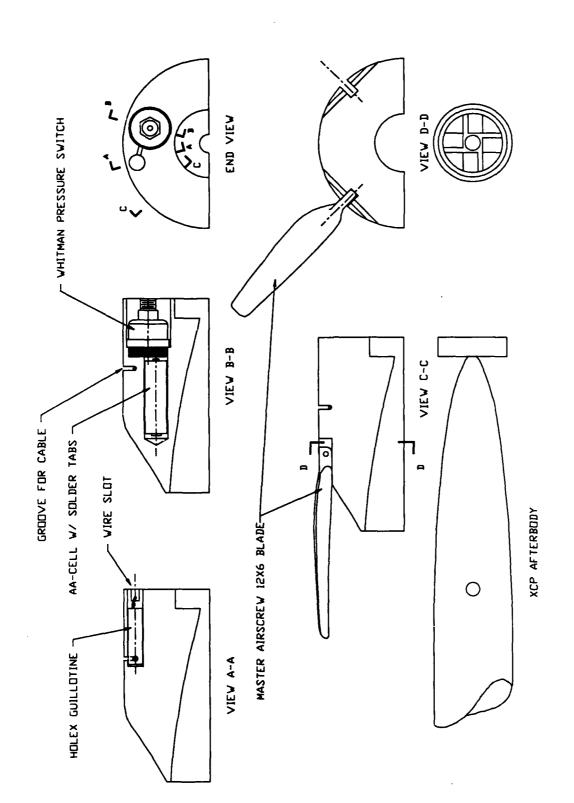
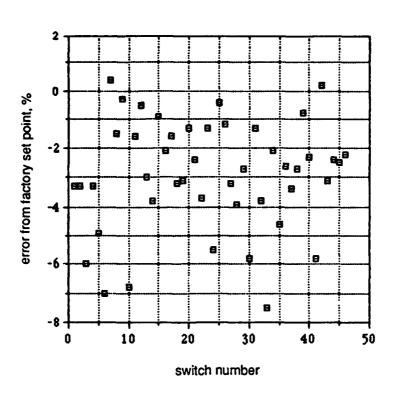*Figure 4. Schematic of release system.*

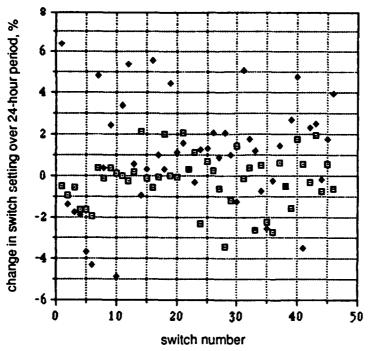*Figure 5. High current pulse output from alkaline AA and AAA cells.*

electrical connections and the back side of the guillotine and pressure switch from the 250 to 300 psi pressure of seawater without resorting to a high precision O-ring sealing system and pressure proof chamber. The encapsulating epoxy was Anchor Seal P/N 6024, a low-stress two-part epoxy mixture.

Five samples of the final prototype were tested in a low-pressure tank at APL. They consisted of the Whitman Controls pressure switch (P/N 1190), a Holex guillotine (P/N 2800), and a Duracell AA alkaline cell. All test assemblies were held at 225 psi for a minimum of 5 minutes, far more than the final system would endure before firing. All fired at the required pressure of 250 psi. Additional tests showed the 0.070 in. diameter, nylon-jacketed stainless-steel cable was easily severed.

According to the manufacturer's specifications, the Whitman Controls pressure switches were accurate and repeatable to within 2% of their factory set point, in our case, 250 psig on increasing pressure. However, when the final lot of 47 units was compared over time intervals of 24 and 48 hours, the switches were neither accurate nor repeatable. In fact, their performance was dismal, with only 20 of the 47 units falling within manufacturer's specifications (Figure 6).

A rapid search was conducted for a possible replacement, and an order was placed with Custom Control Sensors of Chatsworth, California, for their model P/N 607G6, factory set to 300 psig on increasing pressure. Tests showed they were accurate and repeatable ($\Delta T = 24$ h) to within 1% of the set point (Figure 7). The smaller size of the Custom Control switches allowed them to replace the previous ones with minimal modifications.

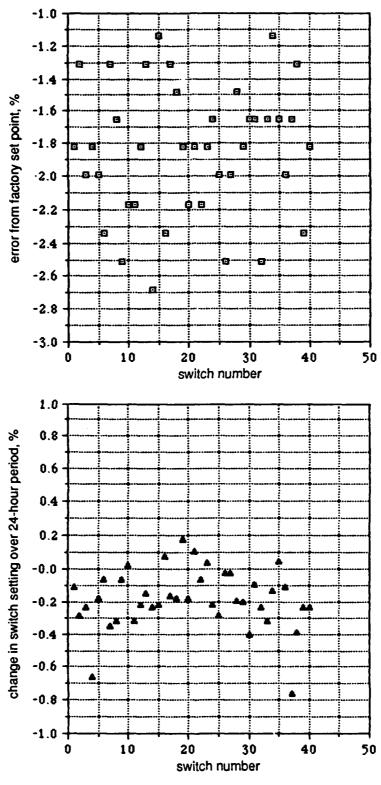*Figure 6.* Data on accuracy and repeatability of the Whitman Controls pressure switch, PIN 1190.

Figure 7. Data on accuracy and repeatability of the Custom Control Sensors pressure switch, P/N 607G6.

ANALYTICAL STUDY

Forces and Moments

Figure 8 is a two-dimensional, free-body diagram of the translational forces and rotational moments acting on the probe and drogue. Figure 9 is a similar diagram of an elemental slice of airfoil. Summation of the forces produces a coupled set of differential equations of motion. This assumes that the simplification to two degrees of freedom is permissible and sufficiently accurate for engineering design.
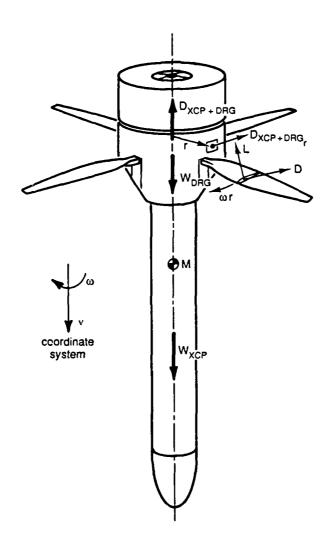

Figure 8. Two-dimensional, free-body diagram of the translational forces and rotational moments acting on the probe and drogue.
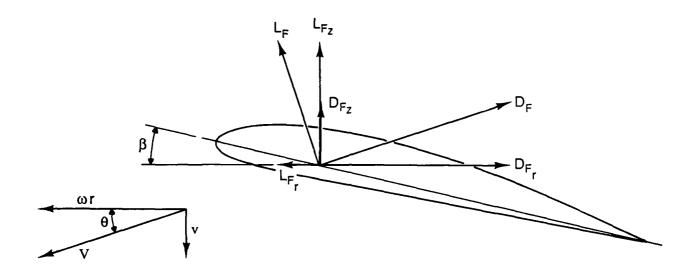
Figure 9. Two-dimensional, free-body diagram of the translational forces and rotational moments acting on an elemental slice of airfoil.

Translational Forces

$$\sum F_z = W_{XCP} + W_{DRG} - D_{XCP+DRG} - D_{F_z} - L_{F_z} = M\dot{v} \, , \tag{1}$$

where

W_{XCP} = weight of XCP, net, in seawater

W_{DRG} = weight of drogue, net, in seawater

$D_{XCP+DRG}$ = drag of XCP and drogue, excluding foils

D_{F_z} = drag of airfoils

L_{F_z} = lift of airfoils

M = total mass, sum of virtual and added masses

v = velocity along probe centerline, positive toward nose .

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Rotational Moments

$$\sum M_z = L_{F_r}(r) - D_{F_r}(r) - D_{XCP+DRG_r}(r) = I_{zz}\dot{\omega}, \tag{2}$$

where

L_{F_r} = radial component of airfoil at given radius

D_{F_r} = radial component of drag of airfoil

$D_{XCP+DRG}$ = radial drag of probe and drogue

I_{zz} = rotational moment of inertia

ω = rotational velocity .

The following section expands on the drag forces and moments due to the XCP and drogue, the drag due to the airfoil, and the lift and resulting moment of the airfoil.

The two static forces are W_{XCP} and W_D, the net in-water weight of the probe and the drogue, respectively. W_{XCP} is initially 909 g in seawater. It decreases linearly with depth as BT wire is payed out. The optimization of the variable W_D will produce the minimum descent speed with a maximum spin rate.

Probe and Drogue Drag

The drag of the XCP and drogue, D, is

$$D_{XCP+DRG} = q\,(C_{D_{XCP}}S_{wet} + C_{D_{base}}A_{base}), \tag{3}$$

where

q = dynamic velocity = $1/2\rho v^2$

$C_{D_{XCP}}$ = drag coefficient of probe and drogue

S_{wet} = wetted surface of probe and drogue

$C_{D_{base}}$ = base drag coefficient

A_{base} = area of base .

Reference 4 gives a simple equation for skin friction coefficient as a function of Reynolds number. At the slowfall speed of 0.67 m s^{-1}, the Reynolds number is approximately 2.44×10^5. Reference 4, Eq. 26, gives an approximation to the Schoenherr frictional coefficient of

$$C_F = [1/(3.46 \log \text{Re} - 5.6)]^2$$

$$= 0.00588 \, .$$

Reference 5 gives an alternate formulation of the turbulent skin friction coefficient of

$$C_F = 0.455/(\log \text{Re})^{2.58}$$

$$= 0.00590 \, .$$

Hoerner (Ref. 4, Section 6-16) modifies this for a cylindrical or projectile-like object by considering its diameter-to-length ratio (0.226).

$$C_{D_{XCP}} = C_F[1+(d/L)^{1.5} + 0.11(d/L)^2]$$

$$= 0.00654 \, .$$

The total wetted surface, S_{wet}, is 1155 square centimeters.

Again, Reference 4, Section 3-19, shows that the base drag is proportional to the ratio of the wetted area to the base area.

$$C_{D_{base}} = C_F \frac{S_{wet}}{A_{base}}$$

$$= 0.0876 \, .$$

This drag results from pressure losses due to a radical change in body diameter such as that considered here or on any blunt-based projectile-shaped object.

Airfoil Drag and Lift

Referring again to Figure 9, equations for airfoil drag and lift can be found as a function of radial distance and velocity. Airfoil drag in the z direction is composed of

both parasitic drag (a combined skin friction and pressure drag) and induced drag due to lift being generated by the airfoil. Both lift and drag increase toward the tip. Parasitic drag in the z direction is simply

$$D_{F_z} = \int_{root}^{tip} q \, C_{D_F} c\,(r)\,dr \sin\theta \,,$$

where

C_{D_F} = drag coefficient of airfoil at given radius

c = airfoil chord

r = radial distance to dr

dr = elemental section of airfoil.

Likewise, airfoil lift is

$$L_{F_z} = \int_{root}^{tip} q \, C_{L_F}(r)\,dr c \, \cos\theta \,.$$

The lift and drag coefficients are a function of the blade section's angle with respect to the incident flow, α. This value varies from blade root to tip as a function of the total velocity vector and β, the angle of twist present in the foil. Lift and drag coefficients are found experimentally using two-dimensional airfoil sections and are tabulated in various handbooks. Section lift and drag coefficients are given as a function of α, where

$$\alpha = \theta + \beta \,,$$

and

$$\theta = \arctan\left[\frac{v}{2\pi\omega r}\right].$$

Ideally, the section characteristics versus radius are known for the given airfoil and are integrated from the blade root to the blade tip to yield an overall lift and drag coefficient. A reference section is taken to nondimensionalize these, usually at $r = 0.7$ of the airfoil span. The moments generated by the lift and drag forces are simply the section forces times their respective moment arms, r.

The two equations of motion (Eqs. 1 and 2) represent a coupled set of second-order ordinary differential equations which can be integrated to solve for v and ω. A simple integration technique such as the Runge-Kutta is sufficient to perform the numerical integration. All the constants of the equations are easily found except for the airfoil section characteristics. Unfortunately, data are not available on the simple model aircraft propeller blades that were candidates for this project.

Theoretically, it would be possible to measure the section shape and angle of attack versus radius — for example, by cutting off successive slices of a candidate airfoil and measuring the section relative to the known airfoil root — and match the results to the closest tabulated airfoil section to obtain section lift and drag data. The two unknowns, v and ω, could be optimized as a function of the variables available, specifically, the volume and density of the drogue and the angle of attack of the candidate airfoils. Given the short-term nature of the Slowfall XCP Program, however, it was decided to abandon the analytical approach in favor of proceeding directly to the experimental testing. The reasons were two-fold: all analytical treatments must be validated at some point with empirical data, and the number of options available was fairly limited and could be covered in an experimental test matrix of acceptable size.

Various propeller blades were purchased for testing. The most promising were two folding propeller blades designed specifically for use on electric-powered model gliders, since they were easily adaptable to the required stowed position.

EXPERIMENTAL TEST PROGRAM
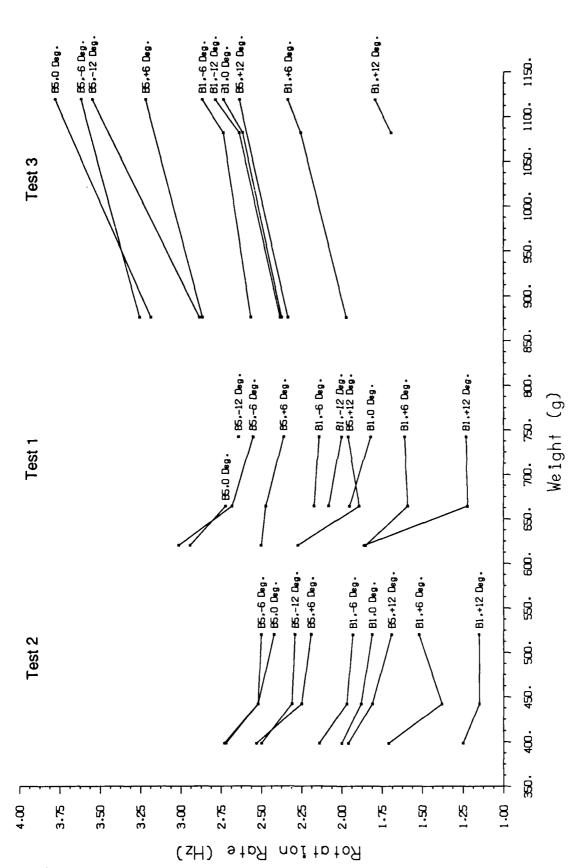
Drop Tank Testing

In the fall of 1986, an agreement was made with the Northwest and Alaska Fisheries Center, a division of NOAA, to use a large steel drop tank at their Montlake facility in Seattle for testing drogue/propeller combinations. This tank, originally constructed for fish studies, is 4 m wide and 10 m deep. It has 12 viewing ports on its three observation floors and has a movable grate floor. Video cameras were used to record the probe's descent velocity and spin rate, as measured with an on-screen timer with a resolution of 0.03 s. Typically four or five rotations and 2 m descent were observable in the camera's field of view.

In all, 174 drops were made over four separate days. Initially it was thought that a positively buoyant drogue would be advantageous in reducing the descent speed. Therefore, the first test was conducted with drogues made of syntactic foam. Three densities were used so that the drag forces would be identical for a given overall volume. Four different airfoils were tested altogether. These were mounted at the top of the drogue in a special fixture allowing all four blades to be rotated simultaneously, and their angle of attack was adjusted in 3° increments. Testing was done over a ±15° range of α. Preference was given to the two special folding propeller blades, and when it became apparent that they performed essentially the same as the standard propellers, tests on the standard propellers were stopped.

Figures 10 and 11 show the results of the first three tests with the two folding propellers (designated B1 and B5), which were conducted in December 1986 and January 1987. The first test (middle column) was conducted with drogues in the 600 to 750 g range. The results indicated that, for a given airfoil at a given angle of attack, heavier drogues produced slower spin rates. This suggested that a more buoyant drogue, with a higher spin rate and lower descent speed, was more desirable.

Several weeks later another series of runs was conducted, this time with drogues in the 398 to 520 g range. The results (left-hand column of Figures 10 and 11) conflicted with those obtained in December, showing that both descent and spin rate were worse with a more buoyant drogue. It was hypothesized (without benefit of analytical tools) that increasing the weight of the drogue caused it to spin faster, and that the additional lift created at the higher spin rate reduced the overall descent speed. Figures 12 and 13 show the spin and descent rates of these three more buoyant drogues as a function of blade configuration at a given angle of attack. The curves definitely do not follow the trend of the previous data. The consistency of the data is fairly good.

One week later another test was conducted with a negatively buoyant drogue and the same two folding propellers. (A negatively buoyant drogue was desirable from an engineering standpoint because it allowed the use of common engineering plastics instead of syntactic or other low density foam.) This time the descent speed decreased as the weight increased (see right-hand side of Figures 10 and 11). Some of these data are replotted in Figure 14 to show rotation rate versus descent speed for a given weight.

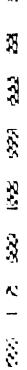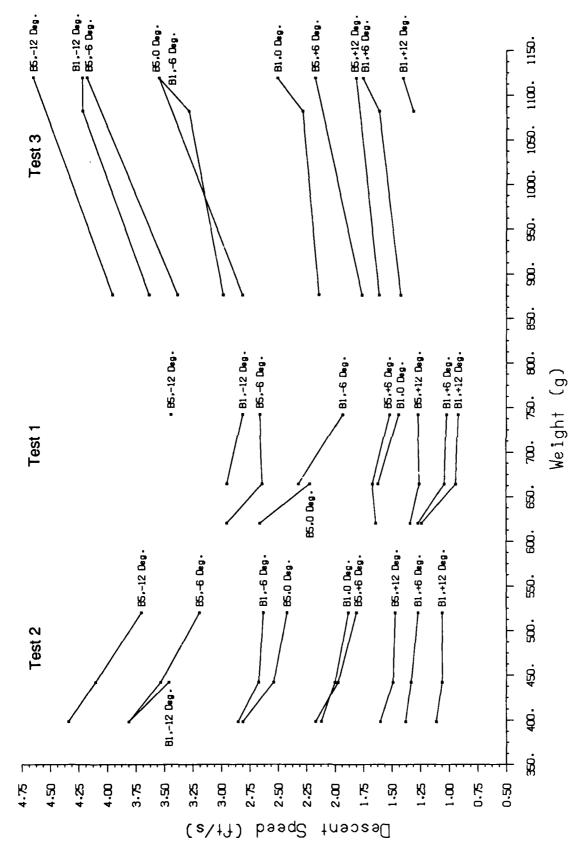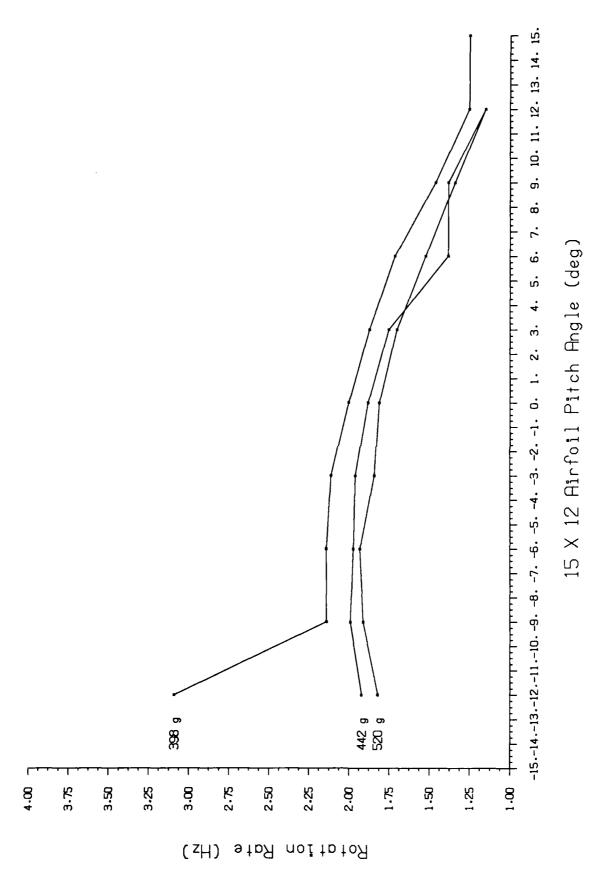*Figure 10. Rotation rate versus system weight for three series of tests on deployable-blade configurations B1 and B5, conducted in December 1986 and January 1987.*

Figure 11. Descent speed versus system weight for three series of tests on deployable-blade configurations B1 and B5, conducted in December 1986 and January 1987.
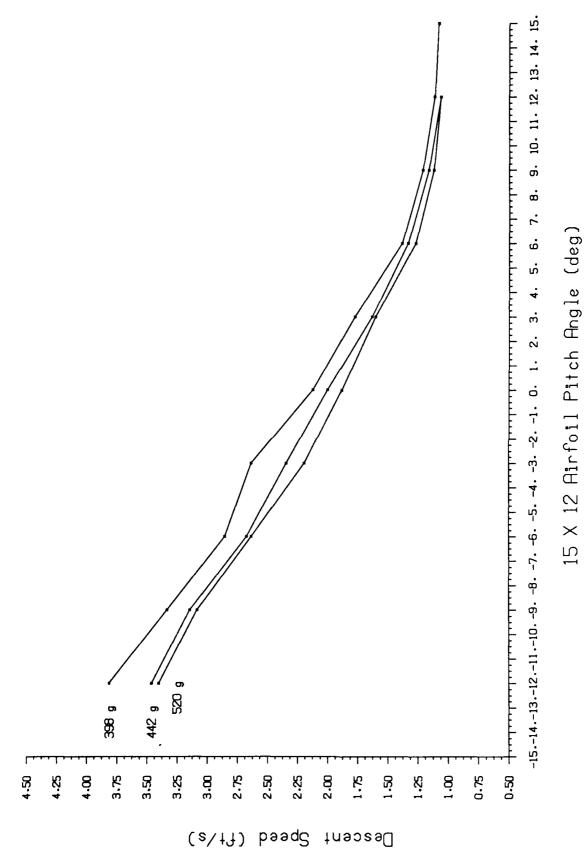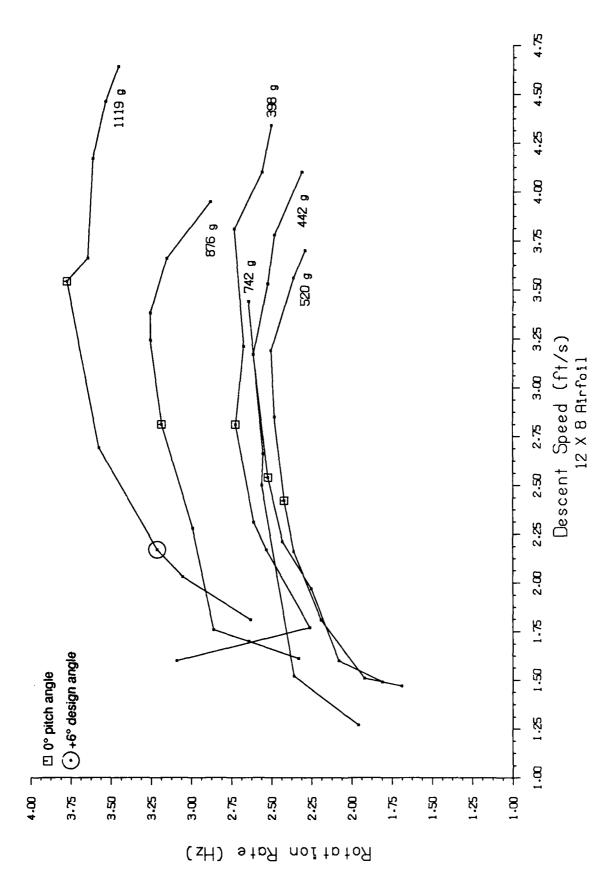
Figure 12. Rotation rate versus airfoil pitch angle for the second series of tests on deployable-blade configurations B1 and B5.

Figure 13. Descent speed versus airfoil pitch angle for the second series of tests on deployable-blade configurations B1 and B5.

Figure 14. Rotation rate versus descent speed for tests with the negatively buoyant drogue.

From this information, we chose a system weight of 1100 g and a blade number 5 set at a +6° angle of attack. The slight feathering of the blade significantly reduced the descent speed while maintaining a sufficiently high spin rate.

Final Drogue Configuration

A survey was conducted of available plastics with the appropriate density, based on the information acquired in the foregoing test. The overall diameter of the drogue was limited by the dimensions of the standard AXCP launch tube. The length was limited by two constraints: The drogue could not extend past the probe's tail, and it should be situated as far as possible from the electrode ports. The tensile and compressive strength need not be high, because the voids for the battery, density switch, and guillotine (on one side of the drogue) and for a stainless steel counterweight (on the other side) would all be sealed with the encapsulating epoxy compound. Precision mounting of the four propeller blades, however, required a dimensionally stable material with good machining properties. A variety of thermoplastic and thermoset plastics were compared for material density, machinability, strength, and cost. Polyvinylchloride was chosen on the basis of its machinability, suitable density, and low cost.

A final test was conducted at the Northwest and Alaska Fisheries Center in May 1987 using a folding airfoil drogue assembled with the release mechanism. Video data of these tests showed acceptable descent and spin rates. The test results are listed in Table I. Figures 15 through 20 were taken with a Hasselblad underwater camera during the tests. In addition to the descent characteristics of the XCP, the performance of an actual modified launch tube was tested. In Figure 15, the launch tube is shown on the surface; the following photographs show the squib firing, releasing the end plug on the launch tube and allowing the probe to fall free.

Table I. Descent and spin rate data from tests with final drogue configuration.

Rate	Descent Speed (m s^{-1})	Rotation (Hz)
Existing XCP	4.5	16
Desired Slowfall XCP	<1.0	>2
Final Slowfall XCP	0.67	3.4

Figure 15. *Photograph of modified launch tube showing end plug.*

Figure 16. *Photograph of release of the launch-tube end plug.*
(A pneumatic blow plug was used to simulate the squib.)

Figure 17. *Photograph of launch-tube end plug falling away, allowing the probe to fall free.*

Figure 18. *Photograph of probe emerging from launch tube and deploying airfoils.*

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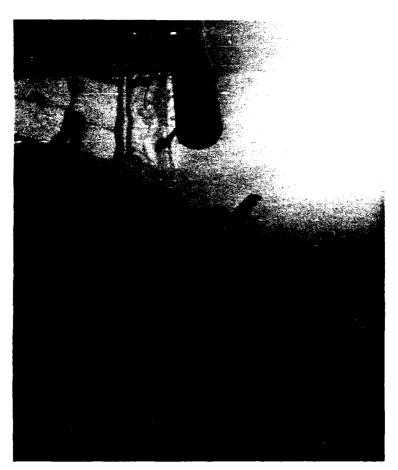
Figure 19. Photograph of probe in slowfall descent.

Figure 20. Photograph of probe in slowfall descent.

NCTES ON MECHANICAL DESIGN

Paramount in the slowfall AXCP design was the issue of cost. Although the least expensive system that will accomplish the desired result is always preferable in any engineering design, it was important to remember that the AXCPs were expendable items that would not be recovered. Therefore, costs were scrutinized more closely than when designing a reusable system.

The number of units to be modified was over 40. This is between a low-quantity semiprototype run and a full-production run where custom-molded or fabricated parts can reduce the final cost per item. For both delivery speed and part quality, individual machining of each component was considered the only option.

Weight Summary

The importance of the drogue's weight has already been discussed in terms of its effect on the descent and rotation rates. The weights of the other components affect the trim of the surface transmitter assembly and its flotation bladder.

The existing flotation bladder responsible for keeping the transmitter housing on the surface and the transmitter antenna above the waterline had little reserve buoyancy. Because the slowfall units were to be used in rough seas, it was desirable to provide as much freeboard as possible to minimize radio telemetry problems. The standard AXCP has 25 to 35 cm of float exposed above the static waterline. With the larger size of the AXCP launch tube and end plugs, plus the significant weight of the drogue itself, this float would be inadequate.

No options were available through SOSI to provide a larger displacement flotation bladder. This left two avenues to achieve sufficient buoyancy: reduce the weight of all APL-supplied components (except for the slowfall drogue) or supply additional static flotation. Eventually, both were deemed necessary to ensure adequate flotation.

Weight reduction dictated selecting different materials for all launch tube components. The most significant change was the use of filament-wound fiberglass for the launch tube. This tube was custom made to the required inside diameter of 10.8 cm. It replaced a bored and turned PVC tube. Although the material density was slightly greater than PVC, the higher strength allowed a thinner wall section (1.6 mm), which significantly reduced the weight. The tubing was strong but difficult to machine (even

with carbide tools) because of its abrasiveness. Handling the tubing was also a problem because of the insidious fiberglass filaments.

The end plugs of the launch tube were made from polypropylene. This not only increased the tube's buoyancy but also eliminated a problem observed in the drop tank experiments when a denser material was used for the end plug: After the squib fired and released the end plug and probe, the plug hit the probe or the deployed airfoils, momentarily stopping the probe's rotation. With a positively buoyant material, the end plug and nose block float up and out of the way of the descending probe.

The collar was made from ABS plastic. This material was chosen over PVC because of its lower density and better machinability. It also provided the option of using an ABS–ABS solvent glue joint between the collar and the SOSI transmitter housing. Sippican personnel routinely use a cyanoacrylate adhesive to bond these parts together.

Despite these changes, the slowfall unit still weighed over 600 g more in salt water than the standard unit. Therefore, closed-cell foam was added to the transmitter housing to provide additional flotation. This material, sized so as not to interfere with the flooding of the seawater battery, provided about 500 g of buoyancy.

Table II shows the final weights of the slowfall AXCP components compared with the original Sippican components. The dry weight of the slowfall unit exceeds that of the

Table II.   Weight summary, in grams.

	Seawater		Air	
	SOSI AXCP	Slowfall	SOSI AXCP	Slowfall
Launch Tube	-14	-216		-457
Transmitter Housing	-809	-809		-1869
Collar	NA	+5		-40
Sleeve	-5	-3		-262
Drogue	NA	-409		-1167
Nose Block	NA	+8		-43
End Plug	-22	+29		-190
Screw	0	0		-13
Foam Collar	NA	+494		+52
Battery	-112	-112		-184
Probe	-909	-909		-1566
	-1871	-1922	-4117[a]	-5843

[a] Estimated

production unit by nearly 2 kg, but the in-water weight is heavier by less than 100 g. (These weights include the probe and drogue.) After a short interval, the drogue and probe are jettisoned, and all flotation problems are eliminated. It is imperative, however, that sufficient flotation be provided to float the transmitter assembly to the surface after the aluminum launch cannister is jettisoned.

One of few differences between the slowfall and standard AXCPs is the use of two squibs to release the end plug in the slowfall version. This was done to minimize the chance of the end plug jamming in the launch tube. The larger diameter launch tube increases the likelihood of an end plug jamming within the tube when supported at only one point. The squibs were connected in parallel and fired from the seawater battery.

Open Water Field Experiment, 13 July 1987

A joint APL-SOSI field test was conducted in Cape Cod Bay in approximately 140 m of water. Sippican provided recording equipment aboard the R/V *SOSI* and a deployment aircraft. Sippican personnel deployed six standard AXCPs, and APL personnel deployed six slowfall AXCPs with 100 psi pressure switches. All six of the SOSI probes performed as expected; however, only five of the six slowfall transmitter units surfaced. The five slowfall units performed as expected, with the drogue being jettisoned at 100 psi.

The probe spin rates were consistent throughout a drop but varied between drops. They tightly circled around two speeds, 3.4 and 3.9 Hz. It is believed that the higher spin rate was due to only three of the four foils deploying. During a test drop at the Northwest and Alaska Fisheries Center, one foil did not deploy, and a spin rate of 3.96 Hz was measured. (Because of the shallow angle of the foil, it may not open if the probe is spinning rapidly.)

Two of the six slowfall units (the failed probe and a 3.96 Hz unit) were early models without springs to aid in foil deployment. In later units, a small rubber compression spring was install . . under the foil near the pivot axis. The spring moves the foil out and away from the probe centerline where, because of the descent velocity, it deploys fully.

Acceleration Measurements

The transmitter assemblies for the six APL slowfall units were instrumented with two single-shot mechanical accelerometers each. These expendable devices are tripped when a shock load on any axis exceeds their trip point. The trip points for the 12 accelerometers were 20, 40, 60, 80, 100, and 150 g, and they were mounted just above the seawater battery. On the five transmitters recovered, all the accelerometers had tripped except for one 150 g unit. (The other 150 g unit was on the probe that sank.)

The terminal velocity of a standard AXCP when using the same parachute system used for the slowfall AXCPs measured about 25 m s^{-1}. For the heavier slowfall AXCP with the same parachute, this would equal a terminal velocity of about 30 m s^{-1}.

RESULTS FROM OCEAN STORMS DEPLOYMENTS

Forty slowfall AXCPs were parachuted from NOAA P-3 aircraft in the air–sea interaction experiment Ocean Storms. Three of these were dropped simultaneously with two regular AXCPs, one each on 23 and 25 October and 21 November 1987; 24 were deployed in a storm on 1 December, and the final 13 the next day. Of the 40 units, 19 provided useful profile data.

Table III summarizes the deployments. Eighteen units provided both temperature and velocity data. Another, No. 2310, provided only current speed (no direction) and temperature. Eleven were never heard from after launch. These are identified in the column headed "No RF" and presumably were destroyed on launch or sea impact or their flotation bags failed to inflate. Five units (labeled "No AF") emitted normal RF signals but provided no AF modulation. It is likely that the BT wire between the surface unit and the falling unit was broken in these instances. Two appeared to produce appropriate RF and AF signals but failed to release the probe and are called "floaters." Three initially returned RF signals (and also AF in one instance) but soon went silent. These are labeled "late sinkers" and are assumed to have sunk because of slow leaks in the flotation bags.

The overall performance of the modified AXCPs was adequate, but the success rate of the channel-12 units was disappointing. It is significant that 11 of 13 channel-12 units either failed outright or produced appropriate signals for only a brief interval. Only 2 of the 27 other units failed immediately.

Table III. Results of Ocean Storms slowfall AXCP deployments.

AXCP No.	Channel	Worked	No RF	No AF	Floater	Late Sinker
2234	12		x			
2268	12					x
2271	12		x			
2274	12		x			
2276	12		x			
2278	12		x			
2281	12		x			
2282	12					x
2285	12		x			
2286	12		x			
2288	12	x				
2301	12		x			
2324	12	x				
13		2	9	0	0	2
2202	14	x				
2264	14				x	
2269	14			x		
227^	14	x				
22⁄ɔ	14	x				
2279	14	x				
2283	14			x		
2287	14		x			
2298	14	x				
2300	14					x
2303	14			x		
2304	14	x				
2328	14	x				
13		7	1	3	1	1
2267	16	x				
2270	16			x		
2273	16	x				
2277	16			x		
2280	16	x				
2284	16	x				
2289	16	x				
2293	16	x				
2296	16	x				
2297	16		x			
2299	16				x	
2302	16	x				
2305	16	x				
2310	16	x[a]				
14		10	1	2	1	0

[a] Missing compass coil (current direction) data

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One way to assess the channel-12 performance is to contrast it with that for channels 14 and 16 using a statistical test. If the success/failure rate distribution is assumed to be binomial, the probability (P) of obtaining r successes in n independent trials is

$$P(r) = \frac{n!}{r!(n-r)} p^r q^{n-r} ,$$

where p is the probability of success in a single drop and q is the probability of failure (i.e., $q = 1 - p$). The expected number of successful drops is

$$\mu = n \, p$$

with an uncertainty of

$$\sigma = \sqrt{n \, p \, q} .$$

The channel-14 and -16 units had a combined p of 0.63. At that rate, 8.2 of the 13 channel-12 units should have been successful with an uncertainty of 1.7.

The probability of only 2 successes in 13 deployments is

$$P(2) = 5.5 \times 10^{-4} ,$$

about 3.6σ from the expected number of 8.2. These results suggest that factors other than our modifications were responsible for the high failure rates on the channel-12 units. One probable cause is failure of the gas release and flotation bag.

Figure 21 compares the velocity profiles obtained from nearly simultaneous drops of two regular units and a slowfall AXCP. The slowfall profile is as initially processed on the airplane and has not been adjusted for gain and phase corrections. The temperature profile obtained from the slowfall unit has been overlaid. The regular probes observed less than a single complete surface wave oscillation, whereas the slowfall unit obtained data over more than four complete cycles in the surface mixed layer. This figure demonstrates the clear advantage of using slowfall AXCPs to separate mean and surface wave motions.

As in the earlier tank and test drops, the rotation rate of the probes varied. It appears that eight units deployed all four blades, eight deployed just three blades, and, in one case, a probe may have deployed only two blades. Figure 22 shows how the frequencies cluster around 3.3 Hz (four blades), 3.8 Hz (three blades), and 4.4 Hz (two blades). The depths shown in the figure are calculated assuming all probes had a fall rate of 0.72 m s^{-1}. If all the squibs actually fired at about 200 m ($\pm$~5 m), the figure shows that fall speed is inversely proportional to the number of blades deployed.
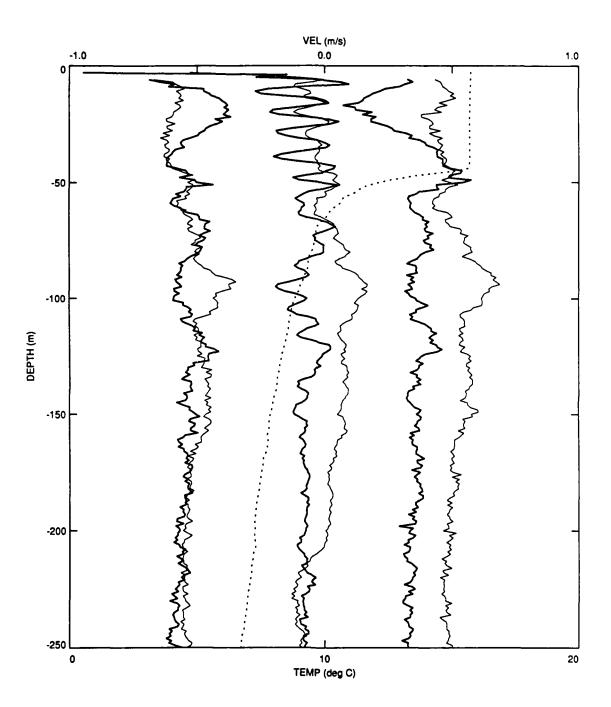
*Figure 21.   Plot of east (heavy line) and north (light line) velocities for slowfall AXCP
2202 (center) and regular AXCPs 2201 and 2203 (left and right). The three
were deployed within a 4 s interval on 23 October 1987. The temperature
profile (...) obtained form the slowfall unit is overlaid. No gain or phase
corrections have been made on the slowfall profile.*

Figure 22. *Squib fire depth versus average rotation rate for slowfall AXCPs. A fall rate of 0.72 m s^{-1} is assumed for all probes in order to calculate apparent depths.*

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None of the units deployed in high winds provided profiles deeper than 1000 m. It is likely that many units expended the wire in the seakeeping (surface buoy) spool. Windage on the surface unit and velocity differences across the base of the surface mixed layer may have required more wire to be payed out than was available. In this case, the wire would break before the AXCP reached terminal depth. Several units experienced a wire break after about 450 s. Assuming that the seakeeping spool had 250 m of wire, the relative motion of the surface units was ~0.6 m s^{-1}. This is about 2% of the 10 m wind speed.

RECOMMENDATIONS FOR FUTURE REDESIGN

The following changes should be considered in any effort to redesign the slowfall AXCP or any similar probe:

(a) Using an AAA alkaline cell as the power source. Although not as robust as the AA, its shorter length would allow a shorter drogue, improving the separation between the drogue and the electrode ports.
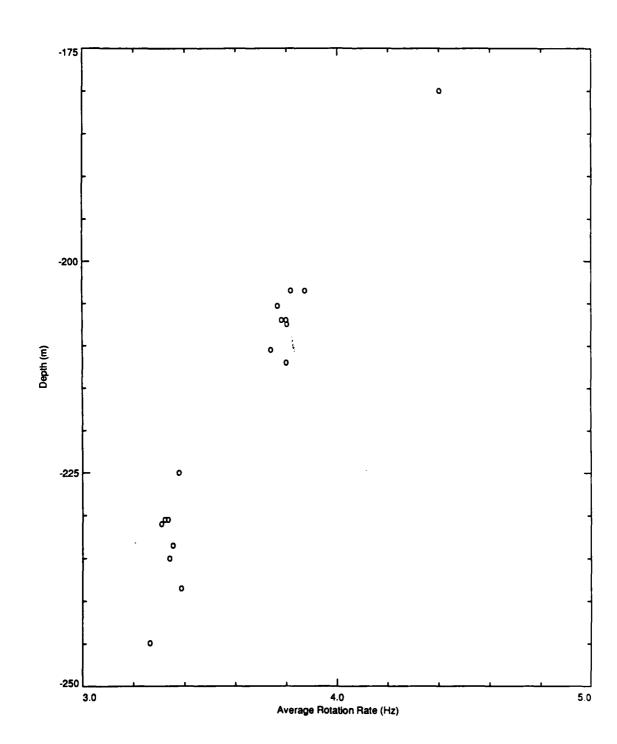
(b) Decreasing the drogue's diameter by 1 or 2 cm to reflect the smaller diameter of the new pressure switch. This would reduce the weight and cost of most components.

(c) Adding a mechanism to assure deployment of all four blades.

(d) Using an extruded plastic or rolled-and-welded aluminum tube instead of the filament-wound tube, which is difficult to machine and handle.

(e) Increasing the size of the SOSI flotation bladder to obviate the need for the supplementary foam collar.

(f) Inserting a cushion of energy-absorbing, collapsible, rigid foam between the bottom of the launch tube and the cannister ballast weight to reduce the peak shock forces.

(g) Eliminating the use of polypropylene or other positively buoyant materials in the end plug. Its permanent mark on some North Pacific beach is a detriment to the scientific ethic.

(h) Adding additional wire on the seakeeping spool to accommodate the large windage and velocity differences in the surface mixed layer. A comfortable length is 3% of 10 m wind speed times 10 min run duration (e.g., 600 m for 30 m s^{-1} winds).

(i) Reducing the 40 s surface delay to a minimum. There is no need for a delay longer than that required to stabilize the battery and electronics.

It is highly unlikely that the unusual failure rate of the channel-12 units is related to the design of the slowfall AXCP. A SOSI effort to rectify this problem is needed.

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APPENDIX

Drawing List No. 42521

DATA LIST		APPLIED PHYSICS LABORATORY UNIVERSITY OF WASHINGTON SEATTLE, WASHINGTON 98105			REV. DATE:	DL 42521	REV LTR

LIST TITLE: XCP SLOWFALL — AUTH. DATE: 10-21-86 — CHGE. CONT NO. — FSCM 98514 — SHT 2 OF ___ SHTS

FSCM	DWG SIZE	DOCUMENT NUMBER	SHT NO.	REV LTR	DOCUMENT NOMENCLATURE	REMARKS
	C	42518			FOIL CLAMP	TEST HARDWARE
	C	42519			FOIL CLAMP, FOLDING PROP	TEST HARDWARE
	C	42520			DROUGE CAP	TEST HARDWARE
	D	42639			DROGUE	
	C	42640			LAUNCH TUBE	
	C	42641			SLEEVE, LAUNCH TUBE	
	C	42642			END PLUG, LAUNCH TUBE	
	B	42649			AIR FOIL MODIFICATION	
	B	42706			PRESSURE SWITCH, MODIFICATION	
	A	42707			SPRING, RUBBER	
	B	42708			NOSE BLOCK	
	B	42709			WIRING FIXTURE	ASSEMBLY TOOL
	E	42710			GENERAL ARRANGEMENT	
	C	42711			COLLAR, LAUNCH TUBE	
	A	42712			COUNTERBALANCE WEIGHT	
	B	42650			COLLAR ASSEMBLY TOOL	

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

XCP	Surface mixed layer
AXCP	Motional induction
Ocean Storms	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Expendable current profilers (XCPs) were modified to fall
slowly (<1 m/s^{-1}) through the upper ocean for the Ocean Storms
research program. The purposes of the modification were to improve
launch and impact survival and to slow the unit significantly so
more cycles of surface wave oscillations could be observed in the
upper 200 m of the ocean. The device was based on a standard air-

(cont.)

20, cont.

deployable XCP (AXCP) manufactured by Sippican Ocean Systems Inc. A drogue was installed on the sensor to slow its descent over a portion of the upper ocean while maintaining a sufficient spin, or rotation rate. At a preset depth, the drogue was jettisoned, and the profiler probe reverted to its normal descent and spin rates.

Forty slowfall AXCPs were deployed in late 1987. Three of these were dropped simultaneously with regular AXCPs. Nineteen units provided profile data. The success rates were 2/13, 7/13, and 10/14 for units operating on sonobuoy RF channels 12, 14, and 16, respectively. The combined success rate for the channel-14 and channel-16 units was 0.63. The probability of obtaining the channel-12 results, (2 of 13), assuming a success probability of 0.63, is <0.1%. These results indicate that the poor performance of the channel-12 units was due to some factor not present in the units at other frequencies. Eleven of the thirteen channel-12 probes failed to produce RF emissions or lost the signals soon after deployment. This mode of failure is unrelated to slowfall modification and suggests failure in the standard gas release and flotation bag system.

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